MesoHABSIM:
A concept for application of instream flow models in river restoration planning

ABSTRACT

This paper describes the methodological concept for application of physical habitat models to restoration planning at a whole river scale. The design proposed here builds upon the Instream Flow Incremental Methodology but is focused at the need for managing large-scale habitats and river systems. It modifies the data acquisition technique and analytical resolution of standard approaches, changing the scale of physical parameters and biological response assessment from micro- to meso-scale. In terms of technological process, a highly detailed microhabitat survey of a few, short sampling sites would be replaced by mesohabitat mapping of whole-river sections. As with more traditional stream habitat models, the variation in the spatial distribution and amount of mesohabitats can provide key information on habitat quality changes corresponding to alterations in flow, channel changes, and stream improvement measures. However, the scale of simulations more closely matches restoration and system analyses, because it provides a solid base for quantitative assessment and simulation of habitat conditions for the whole stream.

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Introduction

River restoration planning demands tools capable of quantifying the consequences of flow and channel modification at various temporal and spatial scales (Naiman et al. 1995). Such tools do not yet exist, but methods like Physical HABitat SIMulation model (PHABSIM) could fulfill this task. However, several issues need to be considered and resolved before instream habitat simulations can be applied for river restoration planning.

PHABSIM was developed in the early 1970s as a planning instrument for negotiations of in- and out-of-stream water use within the framework of the Instream Flow Incremental Methodology (Stalnaker 1995). This technique was originally designed for applications related to individual water use facilities and especially the definition of minimum flow requirements. PHABSIM and other related techniques use high precision measurements of physical conditions to predict flow-based alteration of habitat, together with habitat suitability data for fish. The underlying approach of PHABSIM is to describe these changes with a deterministic hydraulic model, originally developed for flood-control engineering. The choice of this hydraulic technique as the backbone of PHABSIM has been crucial to the entire process and, from a river-scale restoration perspective, a limitation of the model. Still commonly used, a one-dimensional model simplifies low-flow hydraulic conditions because it assumes steady, gradually varied, unidirectional flow (Gordon et al. 1992). The format of the algorithm determines the strategy for sampling channel morphology and hydraulics. Stratified sampling (i.e., transects) typically applied for this purpose is relatively crude and does not properly reflect the curvilinear distribution of hydro-morphologic parameters (LeCoarer and Dumont 1995; Parasiewicz et al. 1999a). Lately, multidimensional hydraulic models have been introduced that incorporate more comprehensive sampling techniques (e.g., Alfredsen et al. 1997). These methods reduce inaccuracy but still do not resolve the problem of high sensitivity of deterministic models to bed roughness, which is particularly critical when calculating low flows. Consequently, high resolution sampling of the bed form is the primary requirement. In more complex systems or where study objectives require habitat assessment in larger areas, the amount of necessary effort makes the application of such models impractical.

To limit the effort to a feasible level in larger scale applications, physical attributes used for model calibration are commonly measured at only a few short sampling sites, and model predictions are then extrapolated to larger segments of rivers and streams. Sometimes, this “representative site” design is supported by rapid habitat mapping to weight the spatial distribution of habitat features. Nevertheless, the accuracy of a river-wide assessment strongly declines during the extrapolation procedure due to variations in stream morphology among sampled sites (Dolloff et al. 1997), and the validity of habitat simulations may depend on the choice of sample locations (e.g., Gore and Nestler 1988; Williams 1996). For all these reasons, physical habitat models frequently are only marginally applicable to large-scale issues and therefore inadequate for system-scale, holistic management.

Another debated aspect of common methods for habitat analysis is the spatial scale of the biological criteria. To merge hydraulic and biological models into a single habitat model, the spatio-temporal resolution of both must match. The observation of fish in microhabitats that are well within the immediate mobility range is largely coincidental. This introduces an error that can be reduced in part by increasing sample size. In larger spatial units, where the animals can be surrounded and captured, the observations are more conclusive. We believe that habitat and fish measurements at larger spatial units would be more practical, more relevant to large scale of management needs, and more conducive to habitat modeling (Hawkins et al. 1993).

In the last few years, alternative physical habitat models have been introduced, improved sampling methods have emerged, and multidimensional hydraulic and ecological models have been proposed (Parasiewicz and Dunbar 2001). Significant effort also has been invested to characterize geomorphologic units or habitat types at scales larger than the micro level (e.g., Hawkins et al. 1993; Jovett 1993; Vadas and Orth 1998). Although numerous studies have reported microhabitat criteria for a wide range of species and life stages, some habitat investigations have pooled microhabitat data to identify community-level habitat-use patterns. Lobb and Orth (1991) identified four key habitat types supporting the fish fauna of a stream. Aadland (1993) identified six habitat types such as pools and runs. Bain (1995) and Bain and Knight (1996) identified five key habitats that supported the greatest diversity and numbers of stream fishes. These and other studies defined meso-scale habitats by analyzing microscale habitat-use data. Another series of investigations (Bain et al. 1988; Kinsolving and Bain 1993; Travnichek et al. 1995; Bowen at al. 1998; Freeman et al. 2000), again using microscale measurements, identified the central role of shallow-water habitat in supporting stream fishes and explaining responses of communities to river regulation (reviewed in Bain and Travnichek 2000). These findings demonstrate that fish-habitat data at the mesoscale are relevant for river management, impact assessment, and fish conservation. Even when microscale data are collected at greater cost and difficulty, investigators and managers have found that results are most easily presented and used at the mesoscale. Finally, simulation of stream fish habitat conditions has been accomplished at the scale above the micro level (Layher and Brunson 1992; Lamouroux et al. 1998).

Here, I present a new concept for handling the physical side of stream fish-habitat relations and a modeling format that will accommodate biological data collection at a scale that is relevant to management. This article describes the methodological concept of a MesoHABitat SIMulation (MesoHABSIM) system that brings habitat simulation to a mesohabitat level by setting the precision of hydraulic sampling to larger units and increasing emphasis of system scale mapping. MesoHABSIM is primarily designed as a method applicable to streams and small rivers, although the general principles are also valid for larger rivers.

The concept

The primary objective of this concept is to promote development and application of habitat assessment procedures that are capable of being incorporated into large frameworks for river restoration. The system should adapt existing techniques to complement methods used to assess ecological integrity (Karr 1981; Muhar and Jungwirth 1998; Jungwirth et al. 2000). We use the mesohabitat approach of Bisson et al. (1982) in the central part of the habitat assessment procedure. Instead of intensively sampling a few representative sites, the survey of physical habitat

Table 1: Definitions of defined mesohabitat types (modified from Bisson and Montgomery 1996 and from Dolloff et al. 1993)

Mesohabitat type	Description
Riffle	Shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient. Convex streambed shape.
Rapid	Higher gradient reaches with faster current velocity, coarser substrate, and more surface turbulence. Convex streambed shape.
Cascade	Stepped rapids with very small pools behind boulders and small waterfalls.
Glide	Moderately shallow stream channels with laminar flow, lacking pronounced turbulence. Flat streambed shape.
Run	Monotone stream channels with well determined thalweg. Streambed is longitudinally flat and laterally concave shaped.
Fast run	Uniform fast flowing stream channels.
Pool	Deep water impounded by a channel blockage or partial channel obstruction. Slow flow. Concave streambed shape.
Plunge pool	Where main flow passes over a complete channel obstruction and drops vertically to scour the streambed.
Backwater	Slack areas along channel margins, caused by eddies behind obstructions.
Side arm	Channels around the islands, smaller than half river width, frequently at different elevation than main channel.

Figure 1. Survey equipment used for habitat mapping consisting of GAC field computer (in the belt), touch pen screen, laser range finder.
The actual position, together with distant locations measured with range finder are plotted on uploaded aerial photograph on the screen, in the hand of Partick Lathion from Geo-Astor AG.

should determine the spatial extent of mesohabitats in the study area under multiple flow conditions.

As described by Hildebrand et al. (1999), habitat sequences often change with discharge level. It is broadly accepted that as flow rises, the distribution of hydro-morphological units will change from riffle-pool towards homogenous run-type habitat (Dunne and Leopold 1978). Hence, the standard hydraulic model can be substituted by quantification of changes in distribution of hydro-morphological units.

For mesohabitat classification, we propose the following hierarchical approach. The reach classification system (Montgomery and Buffington 1993; Arend 1999) is refined to identify high-, moderate-, and low-gradient sub-reaches. Within this framework, the modified and combined systems of Bisson and Montgomery (1996) and Dolloff et al. (1993) can be applied. The hydro-morphological units defined in Table 1 describe spatial arrangement of hydraulic attributes (otherwise determined with transects). This element combined with general notion of magnitude of depth and velocity, and presence of cover parameters, defines mesohabitat type. The number of possible combinations is large and there might be many more mesohabitat types than hydro-morphological units. Their identification is inconsequential because species-specific habitat suitability is the only matter that counts in modeling.

In wadable streams, the spatial extent of individual mesohabitats can be estimated during "river hike," using a combination of aerial photographs, a laser range finder, and a field computer. In addition to describing the size and type of hydro-morphological unit, the extent of cover such as shading, shoreline sinuosity (a function of shore line and river length), and shallow margins are estimated. Random sampling techniques can be applied to obtain the key hydraulic characteristics of the unit. The quantitative distribution of depth, mean column velocity, bottom velocity, and substrate together with secondary attributes like maximum, mean, variance, and Froude number are then used to describe mesohabitats.

Mesohabitat-level biological criteria, even for whole communities, can be relatively easily defined with standard methods (Lobb and Orth 1991; Aadland 1993; Freeman et al. 2000). Multivariate statistics and ecological metrics can be used for habitat quality assessment. Logistic regression is a very powerful tool for this purpose (Guay et al. 1999, Parasiewicz et al. 1999a,b). Established criteria used to describe the suitability of each combination of physical attributes for individual species or whole communities and can be expressed in various forms. The probability of fish presence can be computed from regression equations. The quality of a section or reach of river can be defined by quantifying habitat areas with probabilities higher than 50% at different flows. Another possibility is the use of a normalized suitability index as in PHABSIM. The areas of various mesohabitats occurring at measured flow conditions are weighted by the index and summarized over selected segments or the whole study site. Yet another possibility is the use of landscape metrics like heterogeneity, patchiness, etc. (as in McGarigal and Marks 1995; McGarigal and McComb1995, 1995). Habitat rating curves for specified units can be constructed by plotting suitable habitat area or weighted usable area, or landscape metrics against discharge. This part of the procedure differs from PHABSIM because the rating curves are established for the whole study area.

Biological response to individual restoration measures will be simulated by manipulating the quantity or quality of mesohabitats and temporal or spatial variation of flow. Habitat time-series analyses can be applied to the whole river or selected sections. Restoration scenarios can be simulated to predict the influence of dam removals, enhanced flow regimes, and channel reconstruction on sequences of mesohabitat types and also overall stream habitat quality.

Example of application

The biggest uncertainty associated with this concept is the feasibility and adequacy of data sampling procedure. The previously described method was applied during a river restoration study on the

Quinebaug River, MA and CT. The validity of the assumptions was proved in many cases, and preliminary results are presented to verify the concept discussed above.

The Quinebaug River is a fourth order river with multiple impoundments and a history of industrial use. The river is highly heterogeneous with contrasting gradient and flow conditions. In general, the river is difficult to wade due to cobble, woody debris, and dark "marshy" water.

During the MesoHABSIM survey conducted in summer and fall 2000, 38 km of the river were mapped at low flow with equipment provided by GeoAstor AG (Figure 1). On average, a three person team covered one km per day. After the first survey, the river was delineated into 11 contiguous sections based upon macro scale characteristics (gradient, flow, dominant substrate, cover, etc.). Sensitivity analysis of quantitative distribution of hydro-morphological units was used to identify the shortest representative sites for each section. The sites (combined length—9.2 km) were then surveyed at three different flow releases (0.6 m^3/s, 1.1 m^3/s, and 2.0 m^3/s—regulated at the uppermost dam) (example in Figure 2).

Biological criteria were established with the pre-exposed electro-grids technique described by Bain et al. (1985). In 15 days, nearly 1,800 fish from 17 species were captured at 468 selected mesohabitats. Physical attributes (hydro-morphological unit, cover, and hydraulics) were recorded for each sample. Cross correlation analysis was used to exclude highly correlated parameters and we used stepwise forward logistic regression to identify suitable habitat. Initially, regression analysis was completed for two contrasting species: bluegill (*Leptomis macrochirus*)—a generalist, and fallfish (*Semotilus corporalis*)—a fluvial specialist. The models had high predictive value (>75%) and accurately reflected known biological behavior of these species (Table 3). Bain and Meixler (2000) defined five species (fallfish, common shiner *Luxilus cornutus*, white sucker *Catostomus commersoni*, longnose dace *Rhininchtys cataractae*, and blacknose dace *Rhininchtys atratulus*) that dominated the target community, and these species were analyzed next. The regression equations were then used to determine the probability of fish presence in mesohabitats mapped during the survey of representative sites (Figure 3).

The proportion of wetted area with fish-presence probabilities higher than 50% was summarized and plotted against flow during sampling. The curve-fitted rating curves are assumed to be valid not only for the

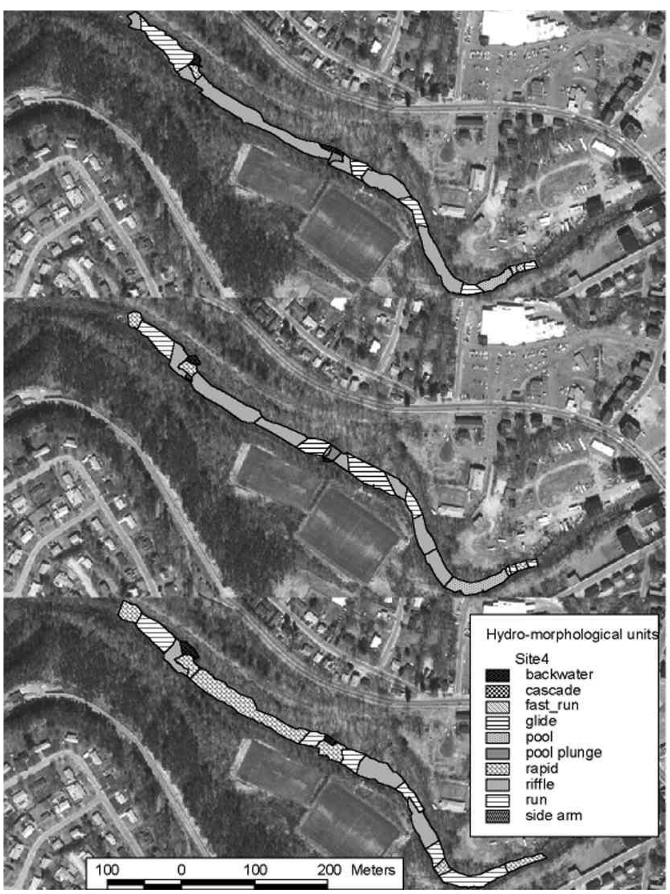


Figure 2. Spatial distribution of hydro-morphological units measured in site 4 of the Quinebaug river during 0.6 m^3/s (top), 1.1 m^3/s (middle) and 2 m^3/s (bottom) release from East Brimfield Lake.

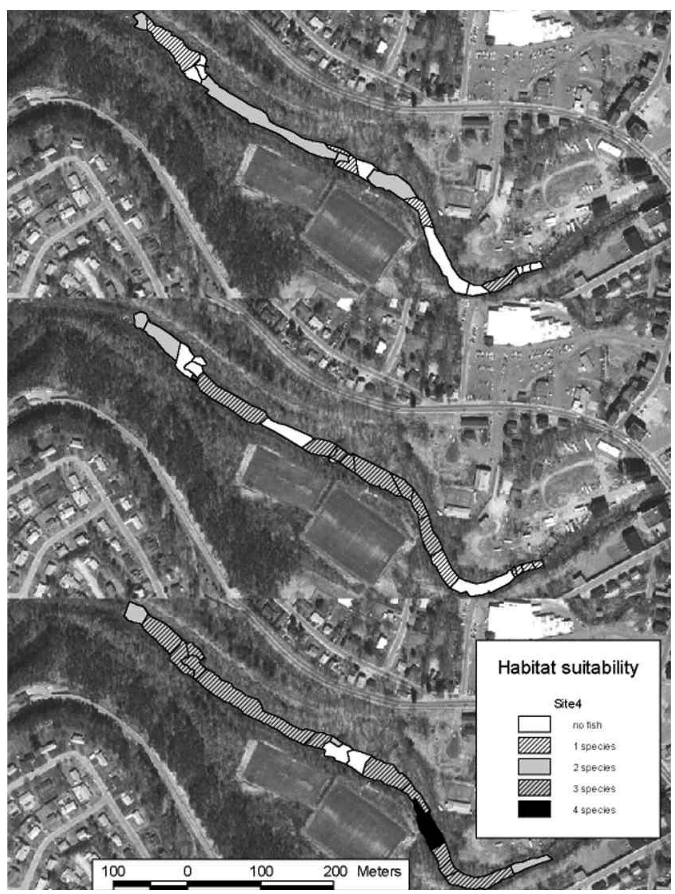


Figure 3. The spatial distribution of habitat suitable for selected community indicating number of supported species.

Table 2: Physical attributes used to establish logistic regression with fish absence and presence.

Attribute (value)	
Categories of Hydro-morphological units (yes/no)	(see table 1)
Cover sources (no/some/much)	Undercut bank, woody debris, overhanging vegetation, submerged vegetation, boulder, riprap, canopy cover shading, shallow margin
Choriotop (% of random samples)	Pelal, psamal, akal, micro-lithal, meso-lithal, macro-lithal, mega-lithal, phytal, xylal, sapropel, detritus (for exact definitions see Austrian Standard ON6232)
Depth (% of random samples)	6 classes in 25 cm increments (range 0–125 cm and above)
Mean column velocity (% of random samples)	8 classes in 15 cm/s increments (range 0–105 cm/s and above)
Froude number	Average

representative sites but for the entire sections. The ratio of representative site length to section length was used as a weighting factor for rating curves constructing a composite rating curve for the whole 38 km long study site (Figure 4). This provided the assessment tool for simulation of various management options such as temporal and spatial manipulation of flows as well as improvements of the riverbed structure.

This study is beginning a second year of data collection and detailed results will be published in the future. Nevertheless, preliminary results definitively prove the feasibility of the concept.

Conclusions and discussion

We have developed a theoretical concept of modeling a river system using physical habitat simulation such as PHABSIM performed at a mesoscale of resolution. This system enhances a widely recognized technique, emphasizes biological requirements for modeling, and includes large scale spatial coverage. It permits quantitative evaluation of management scenarios from the perspective of the aquatic community in the entire river.

The possibility of cross scale analysis that closes the gap between macro- and micro-scale approaches is among the greatest benefits of this approach. In the long run it could provide a way to quantify specific biological response to changes of macro-habitat attributes, for example by coupling indicators of hydrological alteration (Richter et al. 1997) with habitat.

It needs to be emphasized that application of MesoHABSIM is not limited to minimum flow studies, but also allows for predictive assessment of wide range of restoration measures including channel improvements and dam removals. For example, the replacement of the impounded section in the model with the expected habitat mosaic will change the shape of the habitat-flow rating curve and allow for conclusions about ecological benefits prior to demolishing the dam.

The procedural benefits

Mesohabitat scale precision is more efficient for sampling biological data. Species can be captured within the range of their diurnal mobility, thereby reducing bias introduced by temporal and behavioral aspects. For the same reason, the method is better for evaluation. The criteria can be established for individual species as well as for whole communities. Quantitative assessment of prediction validity is an important instrument in adaptive management practice.

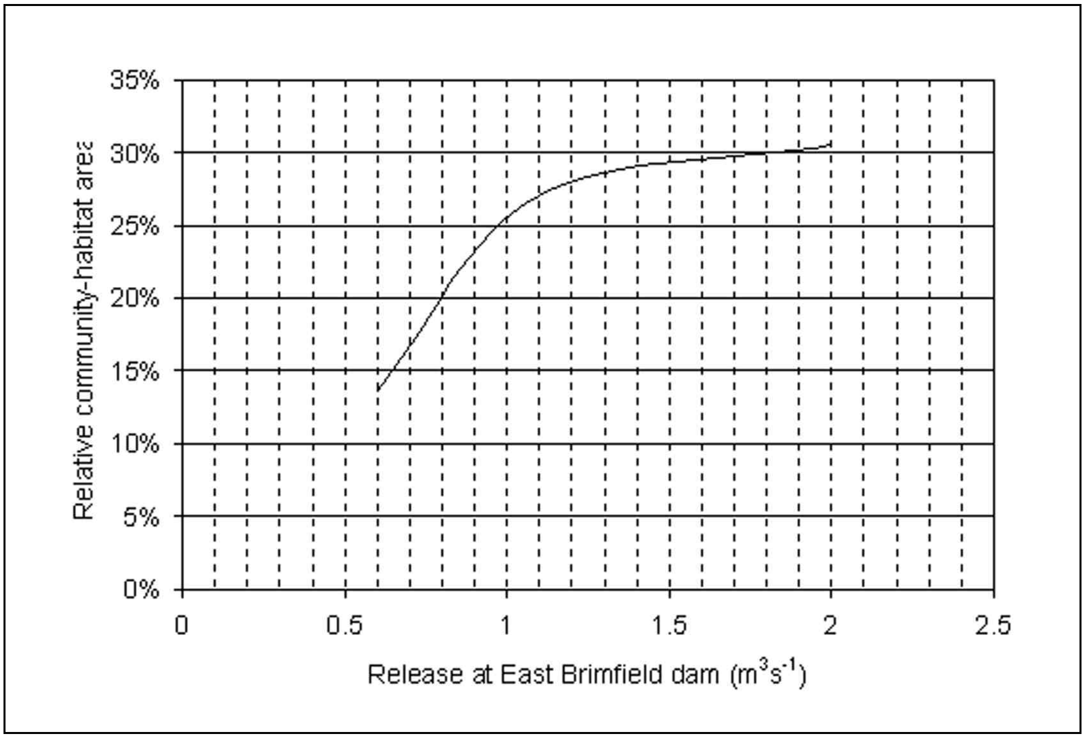
The process of generalizing the results from representative sites to the whole study area is supported by quantitative analysis of habitat distribution. This increases the accuracy of overall assessment due to the reduction of "second-stage sampling error" (i.e., error among the sampling sites, Hankin 1984) and provides sound input for larger scale GIS analysis. This opens new analytical possibilities for combining spatial and ecological metrics with biological response.

The example showed that the technique is effective and provides reasonable results. Within observed flow range, the sensitivity of mesohabitat distribution to flow alteration was greater than expected.

Table 3: The results of regression calculation for bluegill and fallfish. The table shows significant habitat attributes and their beta coefficients. Positive numbers indicate positive reaction and vice versa.

Bluegill		**Fallfish**	
Attribute	Beta	Attribute	Beta
Velocity 15-30 cm/s	2.02	Boulder	1.95
Shading	1.05	Shading	-1.07
Glide	-2.19	Depth 0-25 m	-1.76
Velocity 30-45 cm/s	1.07	Velocity 45-60 cm/s	1.06
Submerged vegetation	-0.75	Run	-0.57

Figure 4. The rating curve of relative habitat area versus flow release for study area on Quinebaug River.

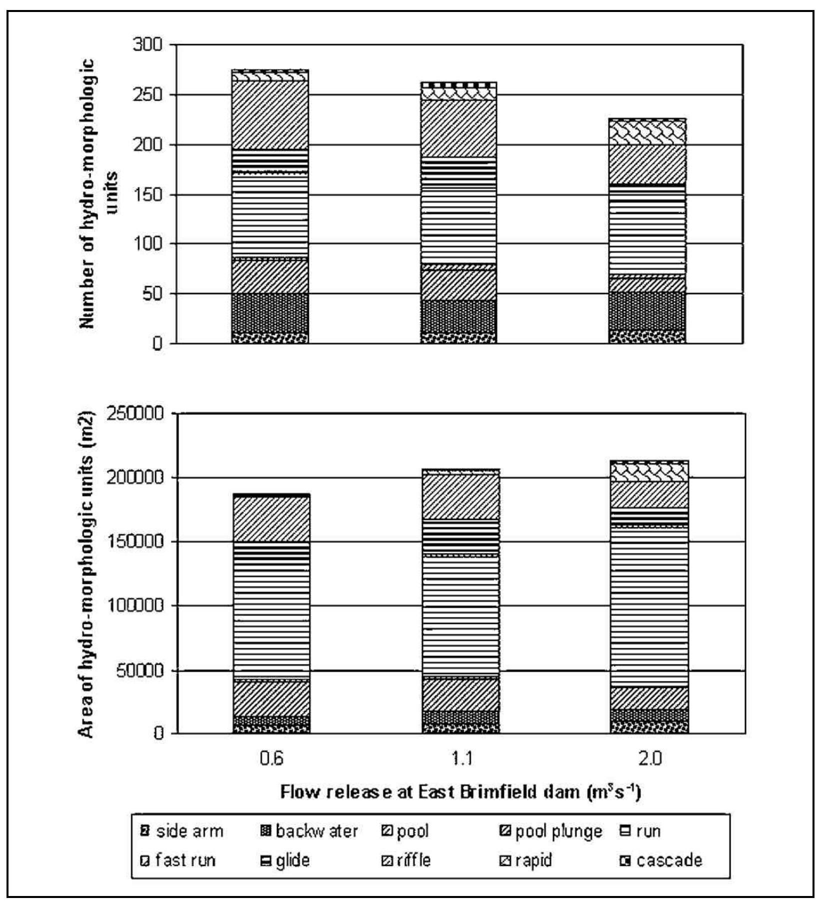


Interestingly, we observed more change in the types of mesohabitats than of their wetted area (see Figure 2). Another observation indicated that the number of hydro-morpholocial units declined (from 276 to 262 to 227) and the areas of run-type habitat increased as flow increased (Figure 5). This observation supports the previously stated expectation that habitat distribution is more uniform and should eventually turn into one dominated by fast runs at higher flows.

This result (also confirmed on two streams in the Catskill Mountains in New York State) suggests that the sampling technique could be simplified. For example, the initial mapping of the river that helps to select representative sites could be reduced to habitat counts only. Furthermore, at high flows mapping could be condensed to relatively crude estimates of habitat areas. The character of fast flowing runs that are frequent during higher flows is relatively uniform and for many species beyond the range of utilization. Detailed sampling might not be necessary to define the habitat suitability of these units. The hydraulic models can be also applied more effectively for high flows because fewer cross sections are needed to provide an accurate model. The remaining refuge areas should be much easier to sample.

The high flow technique has not been tested yet and the present model has proved valid only for relatively small streams at low flow conditions. Nevertheless, the potential for model extension to the different situations exists and is competitive with other existing approaches.

Figure 5. Quantitative distribution of hydro-morphological units at three investigated flow releases. The upper graph shows the changes in the unit numbers and lower in unit areas.



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